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IMPROVED PROCEDURES FOR DETERMINING SEISMIC SOURCE DEPTHS FROM DEPTH PHASE INFORMATION.

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Robert/Bauman

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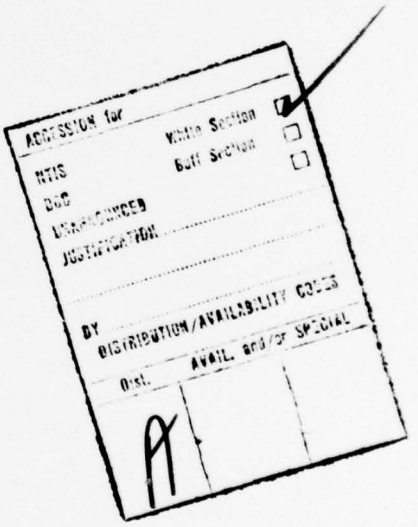

DEPARTMENT OF DEFENSE FORMS

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SUBJECT: Improved Procedures for Determining Seismic Source Depths from Depth Phase Information

AFTAC Project No.	VELA T/6710
ARPA Order No.	2551
ARPA Program Code No.	6F10
Name of Contractor	ENSCO, INC.
Contract No.	F08606-76-C-0003
Effective Date of Contract	1 September 1975
Reporting Period	1 July 1976 to 30 September 1976
Amount of Contract	$73,963
Contract Expiration Date	30 September 1976
Project Scientist	Edward A. Page (703)321-9000

Introduction and Summary

During the last quarter of this contract, differential travel time information for the propagation modes sP-P, sPP-PP, sPPP-PPP, and sPcP-PcP were computed and represented for computer access using a polynominal surface fit. Utilization of this additional travel time information should improve the constructive use of seismic depth phase information contained throughout the coda thereby increasing the percentage of events for which accurate source depth determinations can be obtained. The accuracy of the polynominal surface representation of the computed travel times as well as the accuracy of these travel times in comparison with known sP-P travel times were very good.

Major Accomplishments

A seismic ray tracing program was used to determine the differential travel times for the propagation modes sP-P, sPP-PP, sPPP-PPP, and sPcP-PcP for source depths of 5, 15, 20, 23, 30, 40, 50, 70 and 100 km, and epicenter distances of 10^{o}, 15^{o}, 20^{o}, 30^{o}, 40^{o}, 50^{o}, 60^{o}, 70^{o}, 80^{o}, and 90^{o}. The average earth velocity model assumed was that used to compute the BSSA travel times and the shear wave velocity was determined assuming a Poisson ratio of .25. The ray tracing program was modified to account for the nonspecular reflection at the earth's surface associated with the s-to-P mode conversion. This was done using Snell's low modified for the mode conversion. The remainder of the propagation path was then traced using the P-wave velocity profile.

In Figures 1 through 4 are plots of the differential travel times for sP-P, sPP-PP, sPPP-PPP and sPcP-PcP versus depth and epicenter distance. Comparison of sP-P and pP-P times taken from events in which these phases are clearly defined is in excellent agreement with these computed travel time differences. Figure 5 shows the (sP-P)-(pP-P) delay times for these depths and distances. Tables 6 through 9 show the coefficients for the polynominal fits (which are fourth order in depth and ninth order in epicenter distances) and differences in these surface fits from the computed values. Although these differences occasionally are over .2 seconds, we believe the surface representation to be more accurate than the computed values since the layered earth model often introduces nonphysical discontinuities in the travel time variations.

The addition of these travel times will allow the source depth determination procedure to utilize cepstrum amplitudes associated with these shear wave surface mode conversions and thereby involve more of the available depth phase information in the source depth determination procedure.

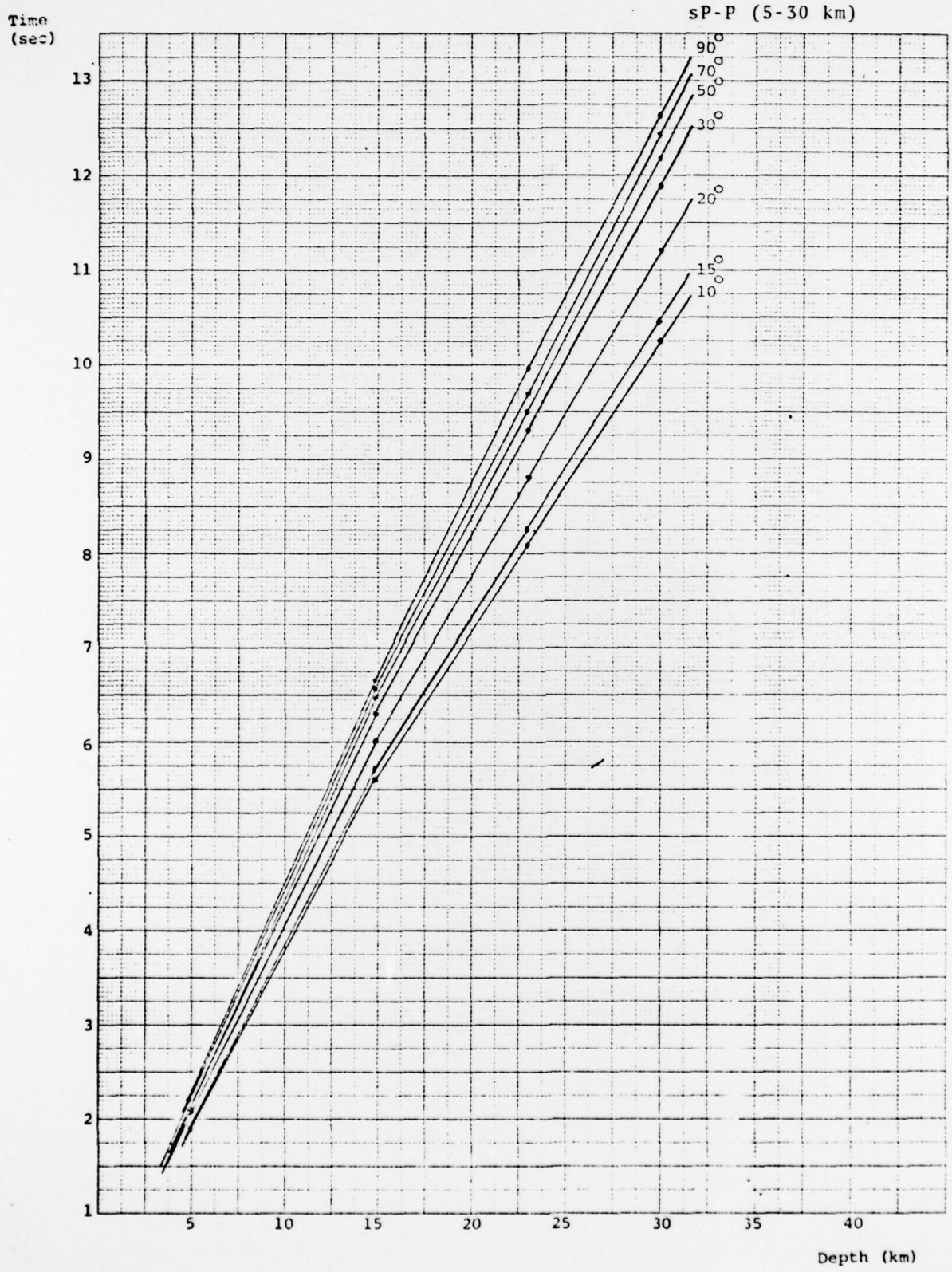
sP-P (5-30 km)
Time (sec)
90°
70°
50°
30°
20°
15°
10°
13
12
11
10
9
8
7
6
5
4
3
2
1
5
10
15
20
25
30
35
40
Depth (km)

Figure 1a

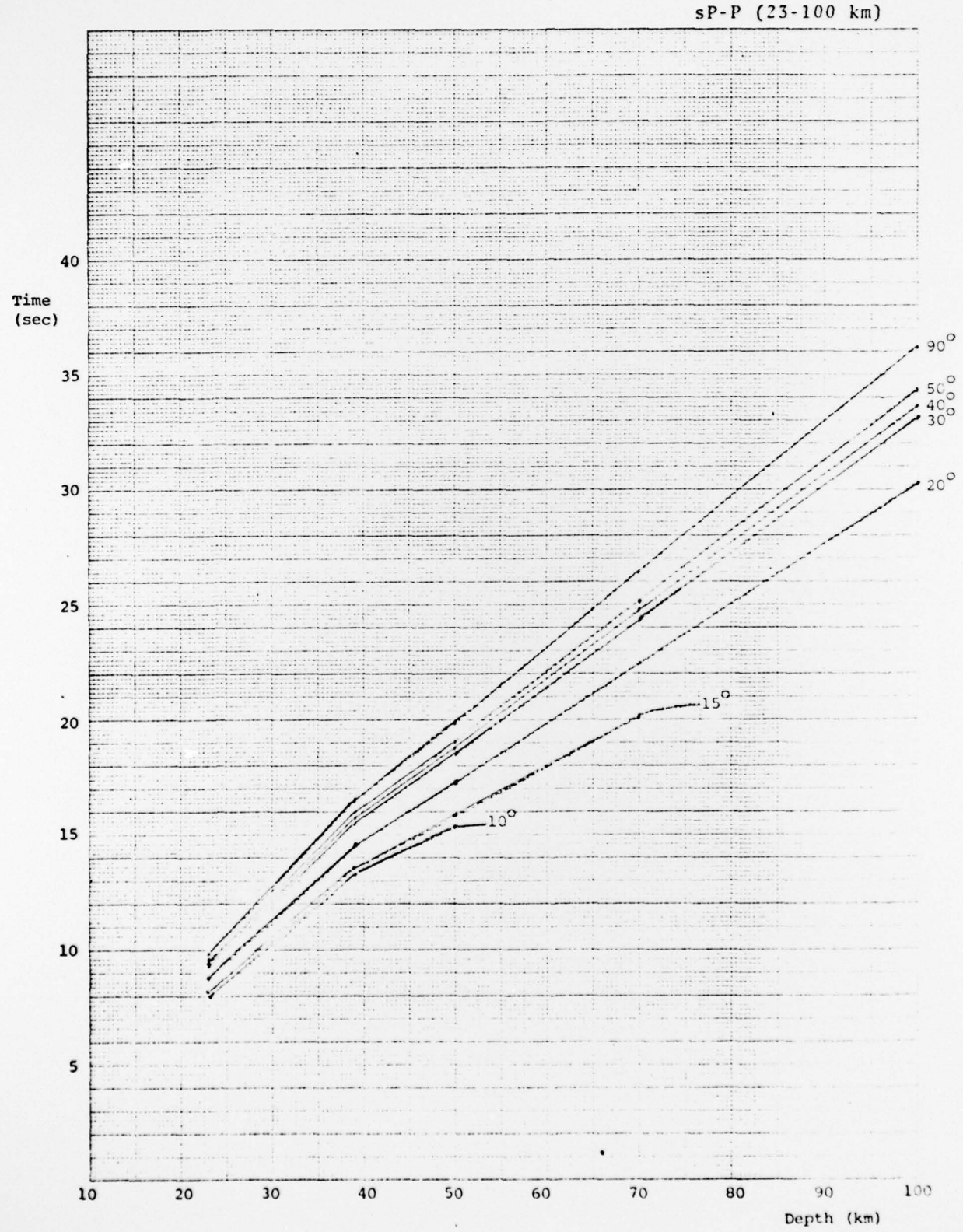
sP-P (23-100 km)
Time (sec)
40
35
30
25
20
15
10
5
10
20
30
40
50
60
70
80
90
100
Depth (km)
90°
50°
40°
30°
20°
15°
10°

Figure 1b

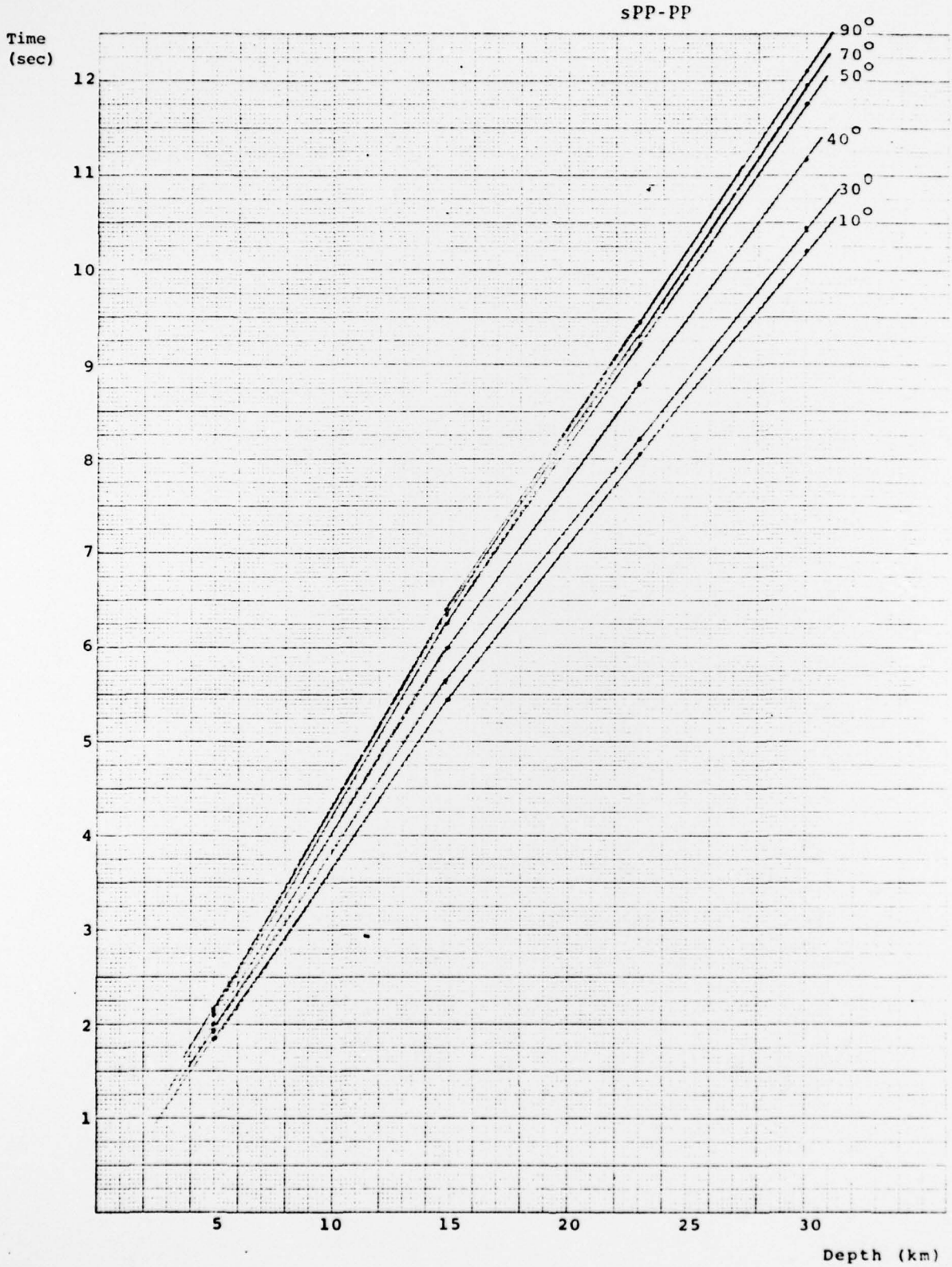
sPP-PP
Time
(sec)
12
11
10
9
8
7
6
5
4
3
2
1
90°
70°
50°
40°
30°
10°
5
10
15
20
25
30
Depth (km)

Figure 2a

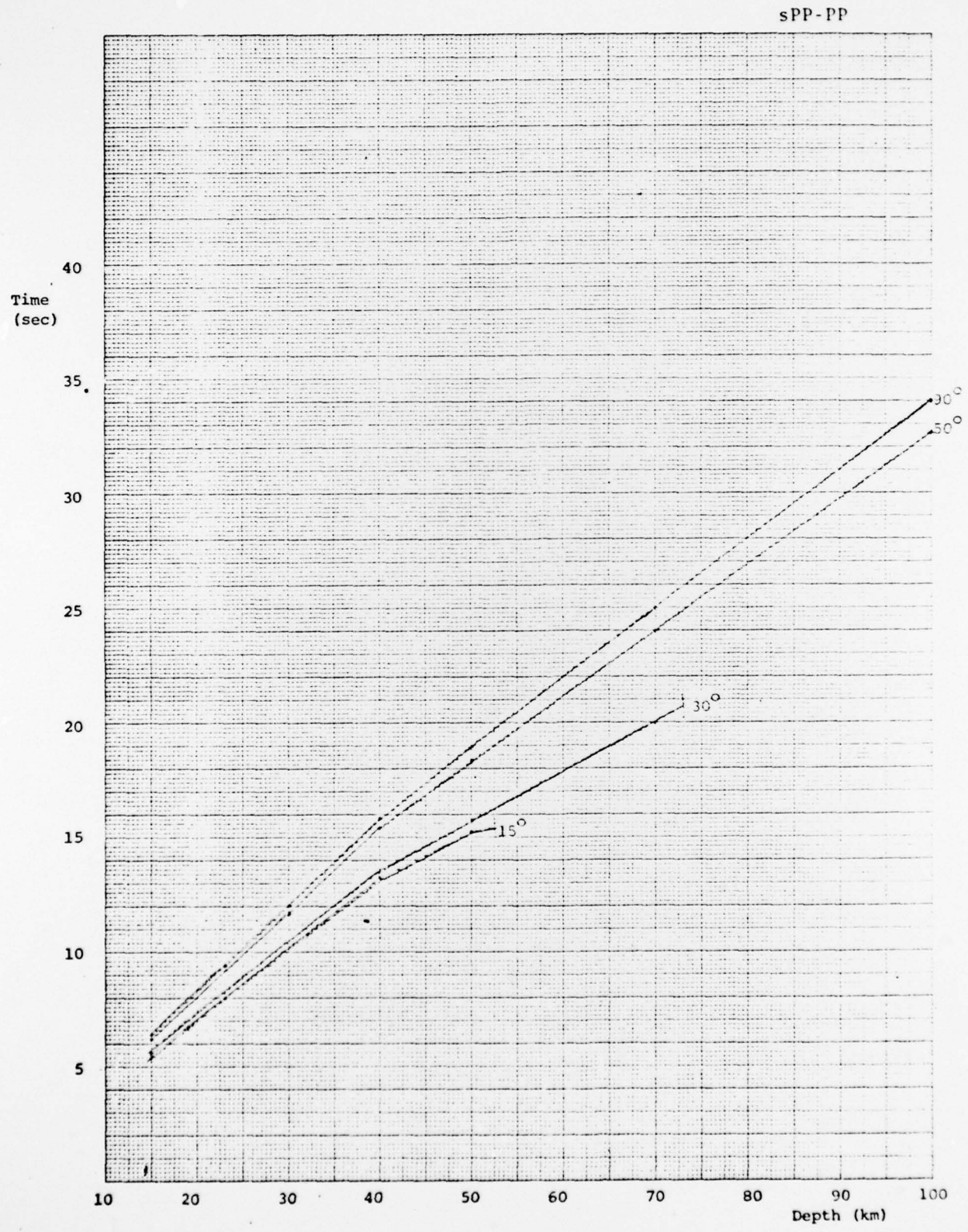
sPP-PP
Time
(sec)
40
35
30
25
20
15
10
5
10
20
30
40
50
60
70
80
90
100
Depth (km)
90°
50°
30°
15°

Figure 2b

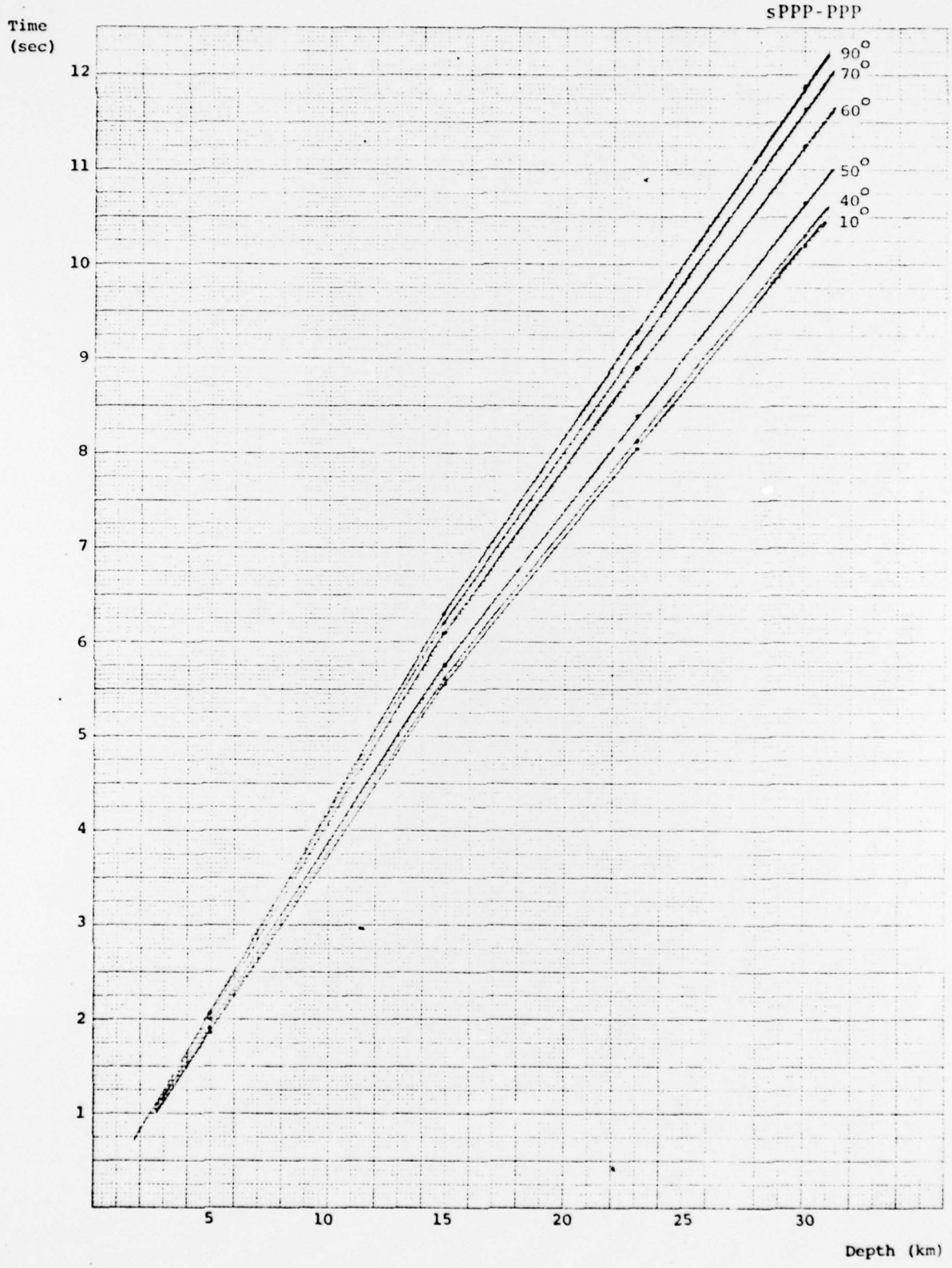
sPPP-PPP
Time
(sec)
12
11
10
9
8
7
6
5
4
3
2
1
90°
70°
60°
50°
40°
10°
5
10
15
20
25
30
Depth (km)

Figure 3a

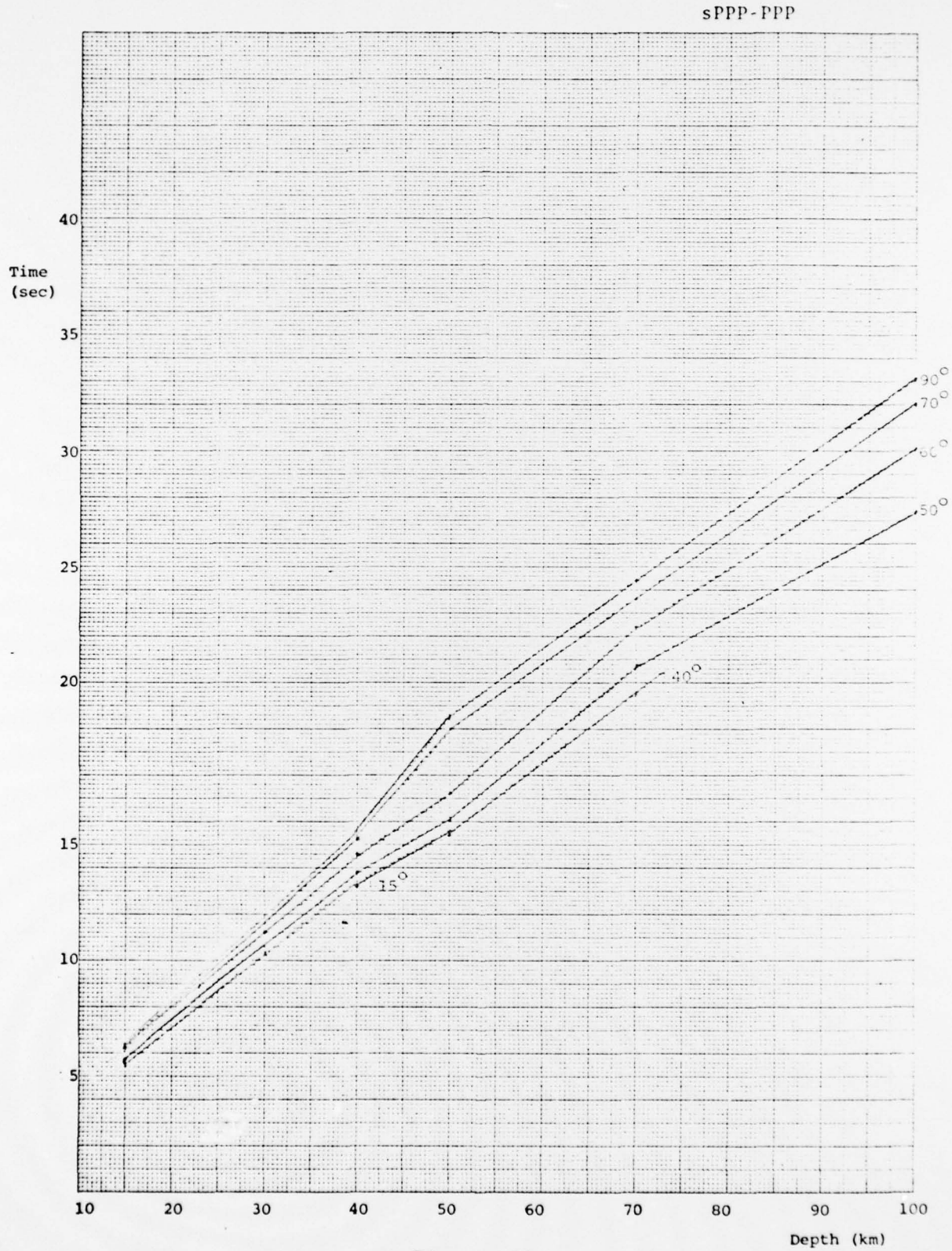
sPPP-PPP
Time
(sec)
40
35
30
25
20
15
10
5
90°
70°
60°
50°
40°
15°
10
20
30
40
50
60
70
80
90
100
Depth (km)

Figure 3b

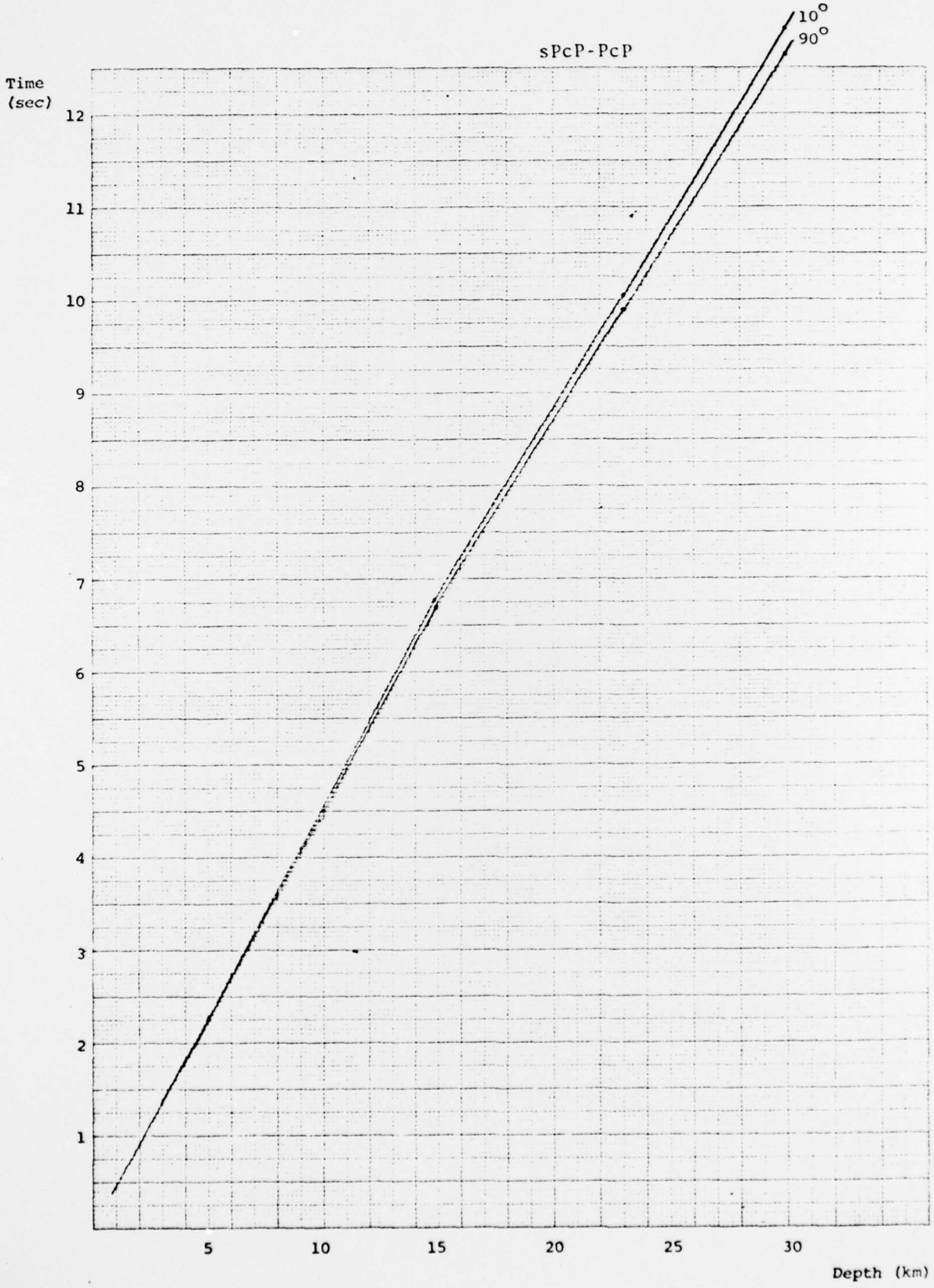
sPcP-PcP
10°
90°
Time
(sec)
12
11
10
9
8
7
6
5
4
3
2
1
5
10
15
20
25
30
Depth (km)

Figure 4a

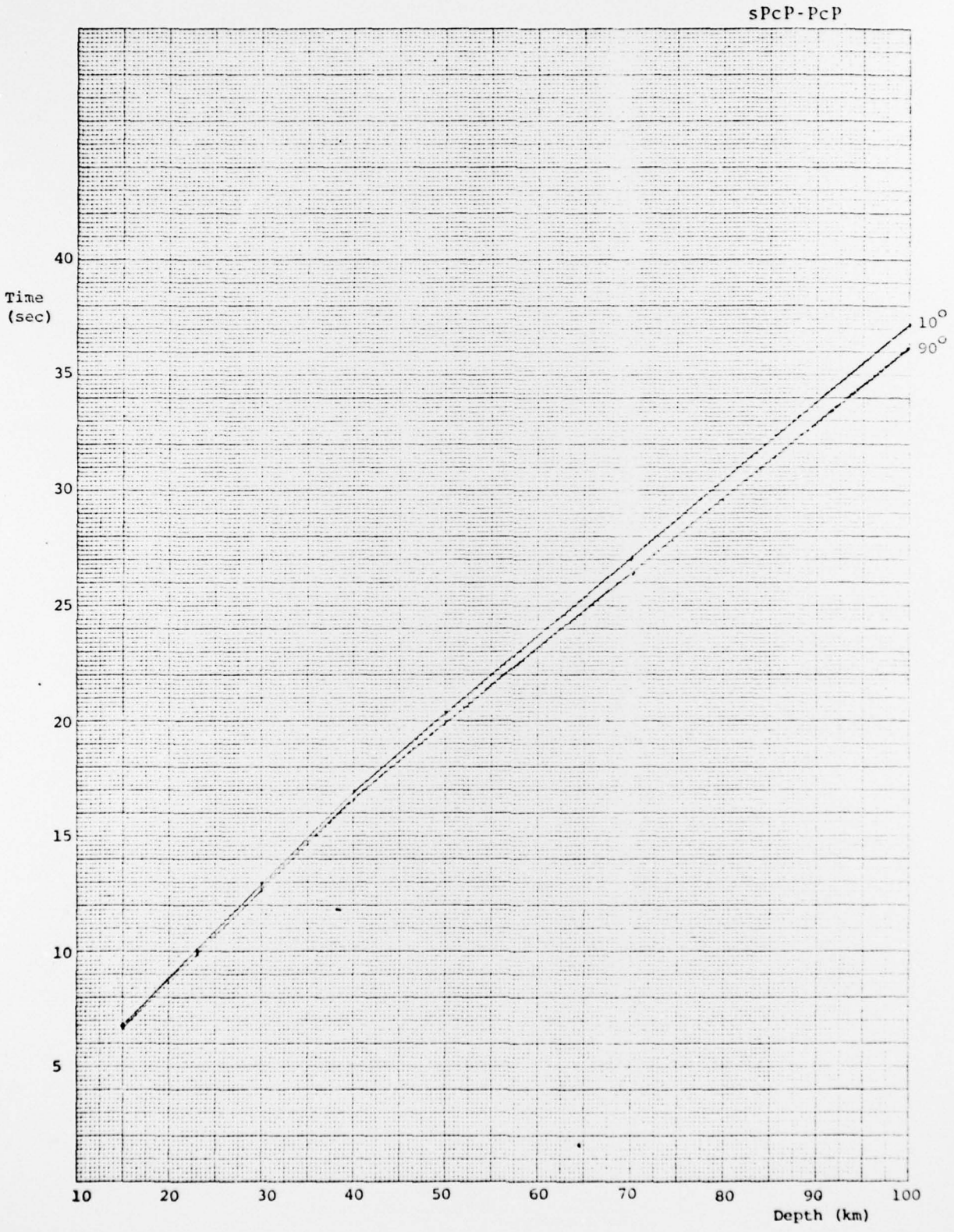
sPcP-PcP
Time
(sec)
40
35
30
25
20
15
10
5
10°
90°
10
20
30
40
50
60
70
80
90
100
Depth (km)

Figure 4b

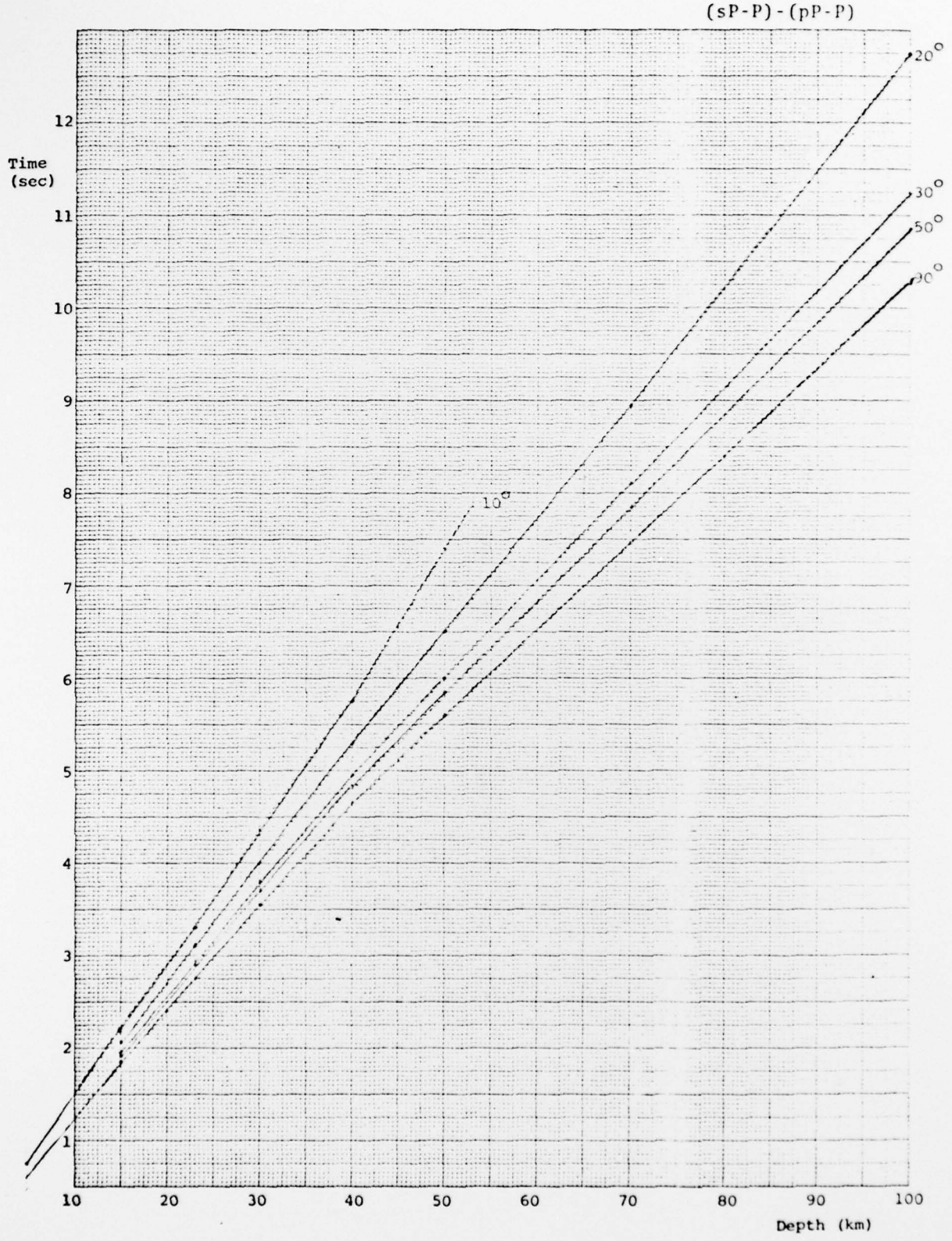
(sP-P) - (pP-P)
Time (sec)
12
11
10
9
8
7
6
5
4
3
2
1
10°
20°
30°
50°
70°
10
20
30
40
50
60
70
80
90
100
Depth (km)

Figure 5

(S↑)P-P TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	.94255761E+00	-.55572891E-02	-.22859618E-04
J = 1	-.17221955E+00	.2441503ZE-02	-.12823485E-04
J = 2	.20157839E-01	-.36968760E-03	.27281394E-05
J = 3	-.12017345E-02	.25614554E-04	-.20722974E-06
J = 4	.42236115E-04	-.99470331E-06	.83545479E-08
J = 5	-.92821287E-06	.23459771E-07	-.20059357E-09
J = 6	.12923121E-07	-.34397382E-09	.29679735E-11
J = 7	-.11085379E-09	.30672552E-11	-.26585638E-13
J = 8	.53483940E-12	-.15241345E-13	.13235732E-15
J = 9	-.11106700E-14	.32361308E-16	-.28128183E-18

CALCULATED TRAVEL TIME DIFFERENCE TABLE (****** MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	1.866	1.968	2.111	2.211	2.229	2.252	2.270	2.291	2.302	2.316
14.900	5.444	5.622	5.987	6.302	6.370	6.438	6.500	6.561	6.601	6.645
23.000	8.191	8.369	8.884	9.397	9.517	9.622	9.725	9.822	9.889	9.960
30.000	10.362	10.565	11.209	11.911	12.083	12.221	12.364	12.491	12.585	12.680
39.900	13.112	13.388	14.251	15.251	15.503	15.689	15.893	16.067	16.201	16.331
50.000	15.347	15.924	17.100	18.446	18.785	19.024	19.293	19.519	19.696	19.864
70.000	*******	19.904	22.177	24.351	24.857	25.223	25.622	25.969	26.228	26.475
100.000	*******	*******	29.116	32.956	33.635	34.274	34.841	35.424	35.773	36.146

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	.019	-.074	-.052	-.100	-.093	-.088	-.086	-.089	-.086	-.085
14.900	.142	.047	.012	.008	.008	.010	.009	.005	.014	.011
23.000	-.005	-.124	-.089	-.093	-.112	-.103	-.101	-.111	-.091	-.096
30.000	-.129	-.107	-.016	-.030	-.060	-.049	-.052	-.066	-.043	-.051
39.900	.203	.183	.354	.277	.210	.239	.217	.198	.222	.214
50.000	-.030	-.143	.158	.055	-.027	.013	-.005	-.007	.002	-.004
70.000	*******	.108	.295	.011	-.106	-.060	-.092	.477	-.076	-.088
100.000	*******	*******	1.157	.150	.031	.032	.022	-.099	.019	.006

Figure 6

(S↑)PP-PP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	.99130961E+00	-.39882993E-01	.88693120E-03
J = 1	-.14539561E+00	.80307558E-02	-.19775324E-03
J = 2	.14753415E-01	-.67171785E-03	.17907379E-04
J = 3	-.85573805E-03	.31364853E-04	-.90225685E-06
J = 4	.31095998E-04	-.93363993E-06	.28400472E-07
J = 5	-.72183911E-06	.18603708E-07	-.58237492E-09
J = 6	.10634489E-07	-.24774913E-09	.77836964E-11
J = 7	-.95966989E-10	.21101808E-11	-.65333857E-13
J = 8	.48325852E-12	-.10348369E-13	.31231642E-15
J = 9	-.10356417E-14	.22134107E-16	-.64780206E-18

CALCULATED TRAVEL TIME DIFFERENCE TABLE (****** MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	1.954	1.858	1.860	1.959	2.113	2.196	2.209	2.221	2.228	2.240
14.900	5.458	5.426	5.438	5.596	5.995	6.258	6.305	6.339	6.366	6.402
23.000	8.068	8.163	8.194	8.333	8.904	9.329	9.411	9.460	9.509	9.566
30.000	10.418	10.339	10.397	10.527	11.248	11.824	11.938	12.002	12.070	12.146
39.900	13.222	13.027	13.144	13.360	14.330	15.139	15.297	15.386	15.481	15.586
50.000	*******	15.182	15.388	15.925	17.242	18.315	18.510	18.633	18.749	18.889
70.000	*******	*******	*******	20.045	22.532	24.207	24.431	24.662	24.787	25.009
100.000	*******	*******	*******	*******	30.078	32.890	32.949	33.500	33.491	33.886

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	-.089	.006	.028	-.067	-.094	-.092	-.102	-.089	-.092	-.085
14.900	.036	.142	.152	.070	.002	-.003	-.002	.006	.011	.008
23.000	-.020	-.094	-.094	-.112	-.109	-.111	-.110	-.107	-.094	-.099
30.000	-.006	-.111	-.123	-.092	-.070	-.058	-.063	-.050	-.048	-.053
39.900	.027	.240	.166	.190	.276	.238	.228	.230	.231	.242
50.000	*******	.055	-.098	-.174	-.012	-.016	-.014	-.012	.006	.009
70.000	*******	*******	*******	-.051	-.115	-.161	-.079	-.128	-.038	-.059
100.000	*******	*******	*******	*******	.091	-.264	.148	-.142	.172	.110

Figure 7

(S↑)PPP-PPP TRAVEL TIME DIFF (SEC) VS+DSPTH (KM) AND DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	-.59770790E+00	.67423860E-01	-.13310196E-02
J = 1	.29276604E+00	-.20371409E-01	.37801578E-03
J = 2	-.13915826E-01	.23180443E-02	-.41281689E-04
J = 3	.2077142?E-02	-.13821156E-03	.23606905E-05
J = 4	-.76039122E-04	.49070703E-05	-.8025280?E-07
J = 5	.17511067E-05	-.10964565E-06	.17146263E-08
J = 6	-.2557049?E-07	.1558?639E-08	-.23303267E-10
J = 7	.2295.989?E-09	-.13688700E-10	.19580996E-12
J = 8	-.11545163E-11	.67671726E-13	-.92810797E-15
J = 9	.2488775?E-14	-.14399043E-15	.18982703E-17

CALCULATED TRAVEL TIME DIFFERENCE TABLE (****** MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	1.959	1.937	1.864	1.865	1.935	2.050	2.149	2.177	2.206	2.209
14.900	5.456	5.501	5.465	5.456	5.529	5.779	6.065	6.203	6.281	6.296
23.000	8.039	8.225	8.272	8.219	8.234	8.534	8.973	9.247	9.356	9.384
30.000	10.146	10.501	10.557	10.423	10.401	10.724	11.299	11.718	11.848	11.889
39.900	13.050	13.693	13.502	13.156	13.198	13.555	14.342	14.996	15.149	15.213
50.000	*******	*******	*******	15.359	15.728	16.172	17.206	18.127	18.298	18.384
70.000	*******	*******	*******	*******	19.776	20.754	22.431	23.894	24.094	24.219
100.000	*******	*******	*******	*******	*******	26.934	30.149	32.245	32.510	32.650

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	-.089	-.077	.006	.027	-.058	-.129	-.135	-.090	-.104	-.104
14.900	.104	.036	.044	.137	.066	-.012	.028	.010	.013	.014
23.000	.019	-.184	-.215	-.114	-.106	-.147	-.058	-.127	-.085	-.085
30.000	.072	-.301	-.351	-.151	-.024	-.078	-.050	-.088	-.009	-.015
39.900	.135	-.461	-.251	.104	.185	.273	.237	.184	.316	.305
50.000	*******	*******	*******	-.502	-.274	-.031	.017	-.077	.125	.106
70.000	*******	*******	*******	*******	-.155	-.057	-.022	-.231	.145	.136
100.000	*******	*******	*******	*******	*******	.504	-.031	-.191	.414	.427

Figure 8

(S*)PCP-PCP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

	TAU SUB 1J	TAU SUB 2J	TAU SUB 3J
J = 0	.47927111E+00	-.19464165E-02	.84976760E-05
J = 1	.12076922E-03	.18634579E-04	-.16407364E-06
J = 2	.77370842E-06	-.16319518E-05	.14444878E-07
J = 3	-.54553179E-06	.68472250E-07	-.62791879E-09
J = 4	.18952584E-07	-.15726234E-08	.15024964E-10
J = 5	-.20217466E-09	.20053550E-10	-.20038010E-12
J = 6	.20008076E-11	-.13305215E-12	.13940850E-14
J = 7	-.55193397E-14	.35763749E-15	-.39361661E-17

CALCULATED TRAVEL TIME DIFFERENCE TABLE (****** MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	2.353	2.355	2.354	2.347	2.340	2.335	2.331	2.329	2.328	2.329
14.000	6.765	6.766	6.758	6.740	6.719	6.702	6.689	6.681	6.677	6.678
23.000	10.150	10.150	10.141	10.109	10.075	10.047	10.026	10.012	10.005	10.005
33.000	12.934	12.934	12.921	12.878	12.833	12.795	12.766	12.746	12.736	12.733
39.000	16.668	16.679	16.666	16.601	16.539	16.486	16.444	16.416	16.401	16.398
50.000	20.313	20.311	20.286	20.209	20.129	20.060	20.005	19.967	19.946	19.933
70.000	27.133	27.124	27.090	26.975	26.859	26.757	26.673	26.613	26.582	26.568
100.000	37.135	37.121	37.064	36.892	36.717	36.567	36.440	36.344	36.304	36.275

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

DELTA → / DEPTH ↓	10.000	15.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
5.000	-.079	-.080	-.081	-.080	-.080	-.084	-.084	-.082	-.087	-.062
14.000	.017	.015	.009	.011	.014	.009	.011	.010	.011	.017
23.000	-.087	-.085	-.102	-.090	-.086	-.097	-.101	-.101	-.106	-.108
33.000	-.054	-.051	-.056	-.052	-.052	-.055	-.053	-.060	-.056	-.058
39.000	.223	.234	.229	.206	.209	.204	.209	.202	.207	.212
50.000	.013	-.009	-.011	-.007	-.005	-.007	-.011	-.010	-.013	-.020
70.000	-.045	-.076	-.116	-.074	-.071	-.078	-.078	-.004	-.087	-.072
100.000	.065	.063	.013	.023	.025	.016	.019	.019	.004	.012

Figure 9